Chapter 3
Fracture Properties Identification using Full-field Measurements: Some Important Concepts and Validation

João Carlos A. D. Filho, Lukas Wittevrongel, Amar Peshave, Pascal Lava, and Fabrice Pierron

Abstract This article studies the effect of Digital Image Correlation uncertainties on fracture parameters obtained from a CT test specimen. It uses synthetic image deformation from finite element simulations to identify such errors. The paper looks at systematic errors from the DIC process as well as the effect of image noise.

Keywords Fracture mechanics · Synthetic image deformation · Uncertainty quantification · Digital image correlation

Introduction

Fracture mechanics is a widely used tool in academia and industry to predict the failure of materials. An important parameter to such models is the fracture toughness in the different modes of fracture, I, II and III. Many techniques have been developed over the years to obtain such parameters, and it is beyond the scope of the present paper to review them. They mostly use the load recorded by the load cell of the test machine together with some (semi-) analytical solutions to derive the fracture properties.

In the last twenty years, full-field optical measurements have gradually spread in the experimental mechanics community, providing very dense sets of kinematic data (typically tens of thousands or more), hence the term 'full-field'. Digital Image Correlation (DIC) is the most widespread [1], with many commercial systems providing turnkey solutions. It is therefore not surprising that many studies have used DIC data to extract fracture parameters, as reviewed in [2]. There are generally two main families of approaches: either fitting the crack-tip displacement field with a Williams series [3] to obtain the stress concentration factor; or using the J-integral [4].

DIC is a complex measurement chain, highly nonlinear and subject to many potential sources of error. As a consequence, while it is easy to process DIC data for stress concentration factors or toughness, it is hard to establish realistic error bars on these quantities. This is the objective of the present contribution. It relies on the technology of synthetic image deformation developed initially in [5, 6] to perform uncertainty quantification in material constitutive model identification with the Virtual Fields Method. It is extended here to the determination of stress concentration factors and J-integrals.

Simulation of DIC measurements on CT specimen

A finite element (FE) model of a Compact Tension (CT) specimen was developed using Abaqus v.6.6, based on the ASTM standard E399 [7]. Plane stress CPS4R linear elements were used. The dimensions and the mesh are reported in Fig. 1. The bottom and top holes were constrained in all translational degrees of freedom, except the top hole vertical displacement which was left free while a vertical load of 35 N was applied. Large transformations were enabled. The material selected for this study is PMMA with a Young's modulus of 3260 MPa and Poisson's ratio of 0.36. The material thickness is 1 mm.

Based on the FE model displacements, a numerically-generated speckle pattern was deformed according to the procedure described in [6]. The pattern was generated with the internal speckle pattern generator in the MatchID software. It consists of

João Carlos A.D. Filho · Lukas Wittevrongel · Amar Peshave · Pascal Lava · Fabrice Pierron
MatchID NV, Leiekaai 25A, 9000 Ghent, Belgium
e-mail: joao.filho@matchid.eu; lukas.wittevrongel@matchid.eu; amar.peshave@matchid.eu; pascal.lava@matchid.eu; fabrice.pierron@matchid.eu

Garrett Pataky et al. (eds.), *Fracture, Fatigue, Failure, Damage Evolution and Thermomechanics & Infrared Imaging, Vol. 4*, Conference Proceedings of the Society for Experimental Mechanics Series, https://doi.org/10.13052/97887-438-0830-5_3

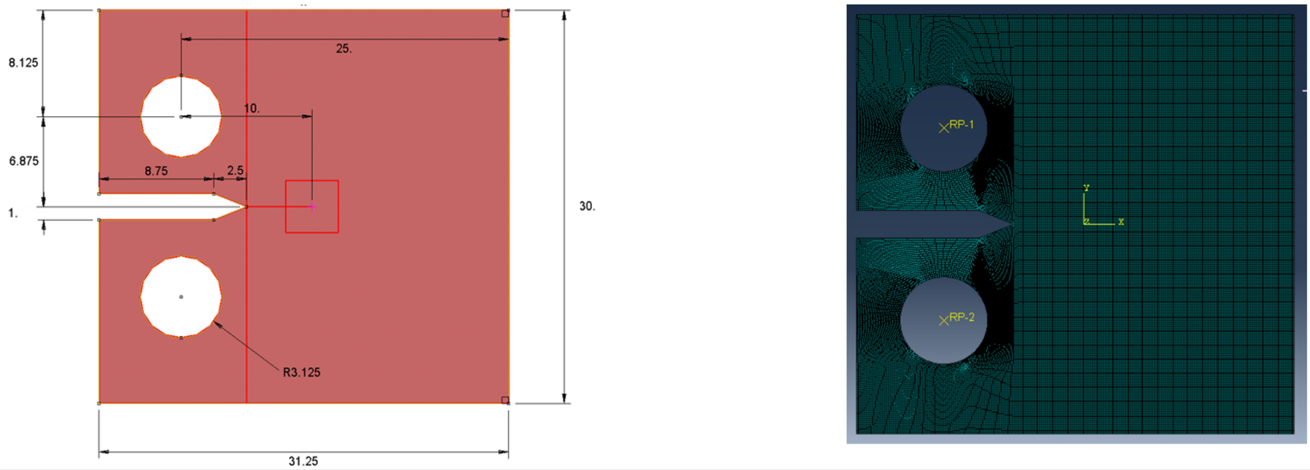

Fig. 1 Dimensions (in mm) and finite element (FE) model of the CT specimen

a regular grid of dots of size about 6 pixels, which centres are slightly moved in a random manner, creating a consistent-size pattern with enough randomness and an isotropic contrast pattern, as seen in Fig. 2. A virtual 8-bit camera of 2448 x 2048 pixels was used to sample the pattern, and deformed images were created for ten load steps from 3.5 to 35 N. The deformed images were then passed through the DIC engine with the parameters recorded in Table 1, according to the recommendations of the DIC guide of good practice [8].

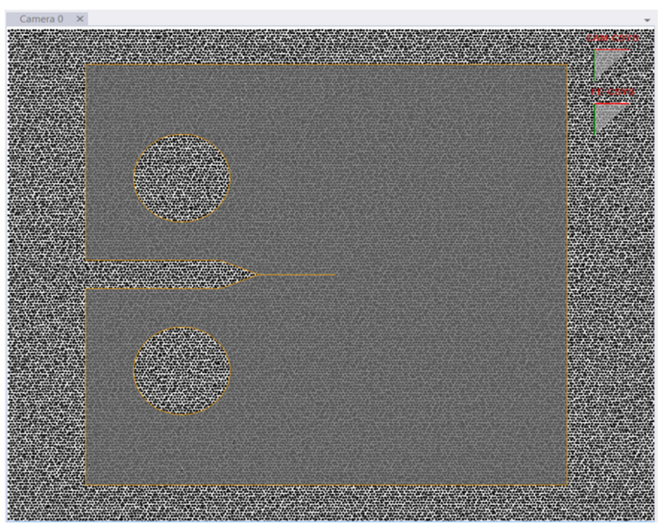

Fig. 2 Image deformation based on the CT FE model

Table 1 DIC parameters

Method	2D DIC
Subset size (pixel)	21
Step size (pixel)	3
Matching criterion	ZNSSD
Shape function	Quadratic
Interpolation	Local bicubic splines
Prefiltering	Gaussian, 5x5 pixels
Strain calculation	Local bilinear polynomial fit
Strain window	3, 5, 7

In the present case, the crack does not grow, the objective was to compare the crack results extracted directly from Abaqus with that from the MatchID crack module and then investigate the impact of the DIC parameters on the results.

The calculation of the stress concentration factor is performed by fitting a 10^{th} order Williams series around the crack tip over the domain visualized in Fig. 3. This is performed in the least-square sense and both K_I and K_{II} are determined. Consistently in this work, because of the test case, K_{II} was found close to zero. For the J-integral, it was calculated over a square path represented in Fig. 3, while the surface J-integral domain is also visible on the same figure, together with the weighing function q which is 0 at the external boundary of the surface and 1 at the internal boundary. It is worth noting that the Williams series fitting is not affected by the choice of the strain window, as it only considers displacements, contrary to the J-integrals. Definition of the contour J-integral and the surface one (also called Equivalent Domain Integral) can be found in [2].

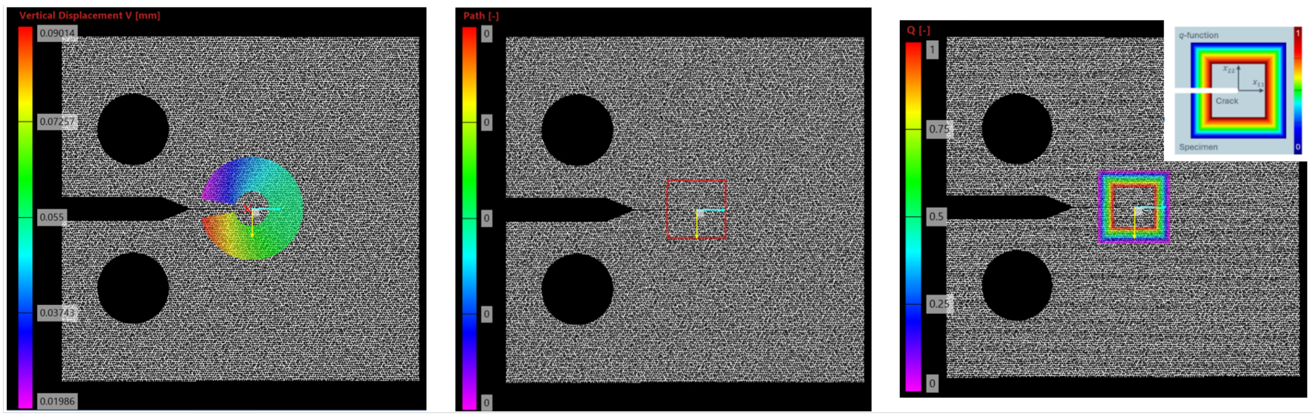

Fig. 3 Williams series domain (left), contour J-integral domain (centre) and surface J-integral domain with the weighing function

Results

The vertical displacements and strains between the pure FE model and the DIC data through image deformation are shown in Figs. 4 and 5 for the last load step at 35 N. The match between the two is clear, though one can see small differences in the strain maps caused by residual interpolation errors in the image deformation process.

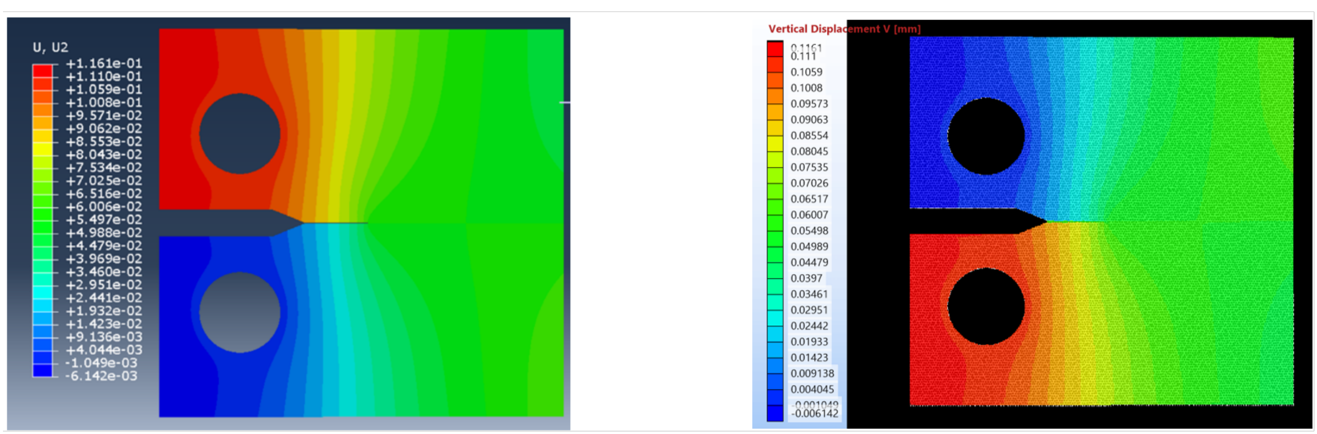

Fig. 4 Vertical displacement maps for the FE model (left) and the synthetically deformed images (right)

The first step consists in a verification of the implementation of the calculations of K and J in MatchID. For this purpose, displacements were directly imported into MatchID and strains calculated as reported in Table 1, with a minimal strain

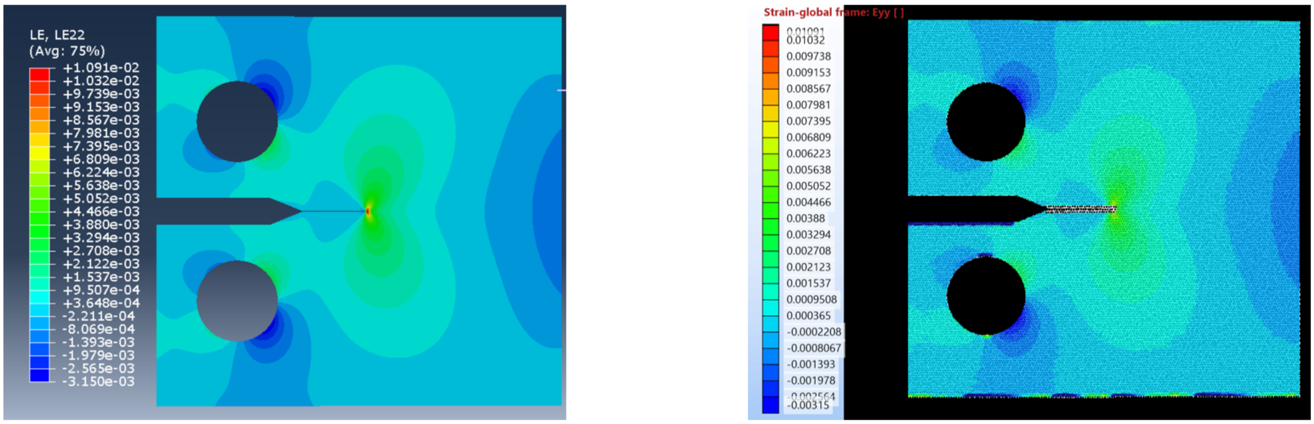

Fig. 5 Vertical strain maps for the FE model (left) and the synthetically deformed images (right)

window of 3. The three fracture metrics (K, J_{path} and J_{frac}) were then compared between the Abaqus and MatchID outputs. The results are provided in Fig. 6.

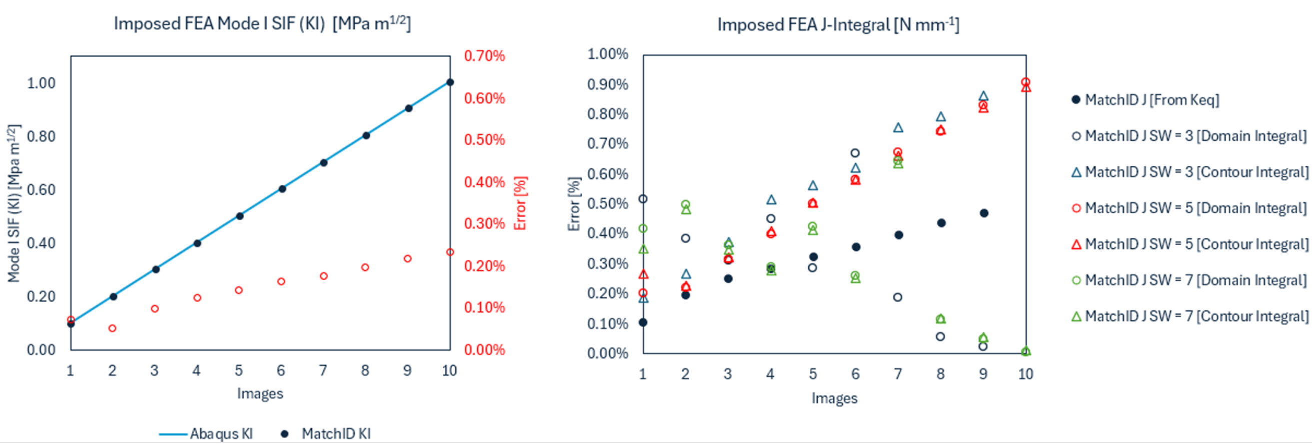

Fig. 6 Verification of the calculation of K from the Williams series (left) and for the J-integrals, for different strain windows. No image deformation, pure FE results loaded into MatchID and strains calculated from displacements in MatchID.

For both K and J-integrals, the differences between Abaqus and MatchID are lower than 1%. There is a limited impact of the strain window too. This result verifies that the MatchID implementation is correct.

The second step is to process the deformed images and compare to the Abaqus results. The data are reported in Fig. 7. For the Williams series, the errors are very similar to that obtained from the pure FE data but there are some larger errors at small loads (small strains) on the path J-integrals. These are caused by edge outliers over the faces of the crack. It is worth noting that the surface integrals do not suffer from these effects as the spurious edge data average out. It is also worth noting that for higher loads, this effect becomes negligible.

Finally, the effect of camera noise was simulated by polluting each image by a Gaussian distribution of noise of zero mean and 1.5 grey level standard deviation for the 8-bit images, a realistic noise level for modern CMOS sensors. The results are summarized in Fig. 8. K is not affected by the camera noise as it bears only on displacements and a large number of points are used for the fit. This is a clear advantage of it. The contour J-integral is the most sensitive to noise as it does not use a lot of (noisy) strain data points, while the surface J-integral is more robust to strain noise. One also sees a reduction of noise with the strain window, as expected. From these results, the advantage of the surface J-integral formulation vs the contour one is clear.

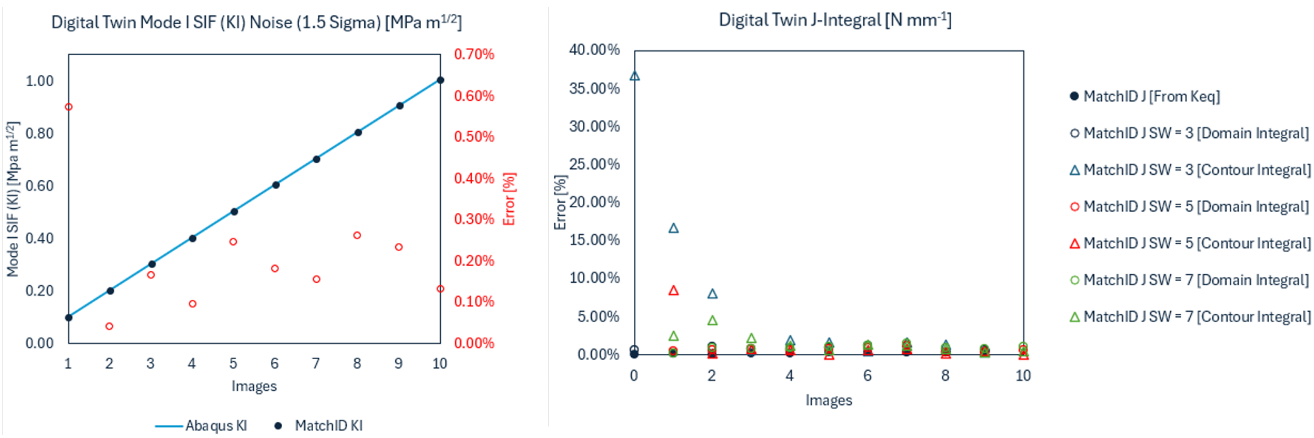

Fig. 7 Error on K (left) and J-integrals (right) for different regularizations (strain windows)

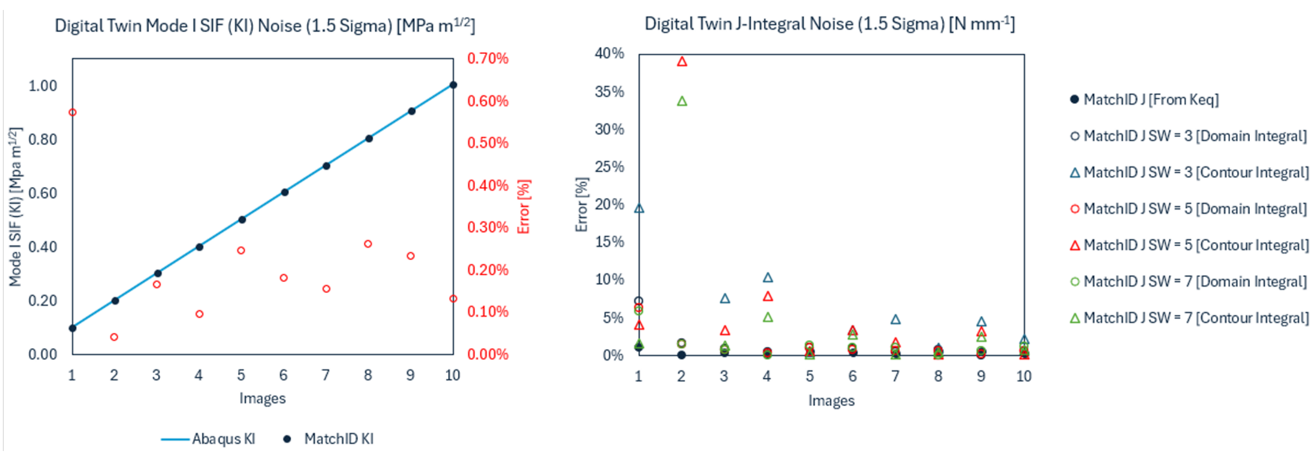

Fig. 8 Error on K (left) and J (right) obtained from noisy images

Conclusion and Future Work

This paper presented a preliminary study on the use of synthetically deformed images to investigate the errors generated by the use of Digital Image Correlation in extracting fracture parameters from fracture tests. The first results are consistent with expectations:

- the formulations in the MatchID software have been verified with the finite element model;
- the Williams series fit to obtain K is much less sensitive to noise in the data as it only uses displacements. However, K only provides an estimate of the fracture toughness;
- the surface J-integral (or Equivalent Domain Integral) is much more robust to strain outliers and noise;

Synthetic image deformation is an ideal tool to investigate systematic and random errors in fracture mechanics parameters obtained from DIC. In the future, effects of imperfect boundary conditions, presence of plasticity at the notch root, crack propagation and other fracture test configurations will be investigated. More realistic DIC errors will also be considered [9].

References

1. Sutton, M.A., J.J. Orteu, and H.W. Schreier, Image correlation for shape, motion and deformation measurements: basic concepts, theory and applications. 2009, New-York: Springer. 1-321.
2. Becker, T.H., Extracting fracture properties from digital image and volume correlation displacement data: A review. Strain, 2024. 60(4): p. e12469

3. Williams, M.L., On the stress distribution at the base of a stationary crack. Journal of theoretical and applied mechanics, 1957. 24(1): p. 109-114.
4. Rice, J., A path-independent integral and the approximate analysis of strain. Journal of applied mechanics, 1968. 35: p. 379-386.
5. Rossi, M. and F. Pierron, On the use of simulated experiments in designing tests for material characterization from full-field measurements. International Journal of Solids and Structures, 2012. 49(3-4): p. 420-435.
6. Rossi, M., et al., Effect of DIC spatial resolution, noise and interpolation error on identification results with the VFM. Strain, 2015. 51(3): p. 206-222.
7. ASTM, E399 - Standard test method for plane-strain fracture toughness if metallic materials. 1990, Amercian Society for Testing and Materials.
8. Jones, E.M.C. and M.A. Iadicola, A Good Practices Guide for Digital Image Correlation. 2018, International Digital Image Correlation Society.
9. Peshave, A., et al., Practical Uncertainty Quantification Guidelines for DIC-Based Numerical Model Validation. Experimental Techniques, 2025. 49: p. 437-457.